Spatial resolution of near-field scanning optical microscopy with sub-wavelength aperture

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The finite-difference time-domain (FDTD) method is employed to solve the three dimensional Maxwell equation for the situation of near-field microscopy using a sub-wavelength aperture. Experimental result on unexpected high spatial resolution is reproduced by our computer simulation.

§1. Introduction

Near-field scanning optical microscopy (NSOM) [1),2)] is a powerful tool for the study of nanometer features with spatial resolution of 50-100 nm. The heart of NSOM is a near-field probe, which is a metal-coated optical fiber tapered to sub-wavelength aperture. When the probe end approaches a sample surface, the object is illuminated and the reemitted light is collected in the near-field region of the aperture, whose diameter determines the spatial resolution of NSOM. Optical imaging beyond the diffraction limit is carried out by scanning the probe on the surface. In addition to this fundamental principle, the resolution of NSOM is also subject to the tapered structure of the probe. Such a behavior has been demonstrated through our NSOM spectroscopy of single quantum dots. [3),4)]

Numerical analysis of electromagnetic field in the vicinity of the aperture and propagation property of light in the tapered waveguide is quite advantageous for the understanding of experimental results. We employ the finite-difference time-domain (FDTD) method [5)] in the Mur absorbing boundary condition [6)] to solve the three-dimensional Maxwell equation for the same situation as the experimental configuration and discuss the validity of simulation results.

§2. Calculations

Figures 1 and 2 show the geometries of the problem. A near-field fiber probe with a double tapered structure collects luminescence ($\lambda = 1\mu$m) from a quantum dot buried $\lambda/10$ beneath the semiconductor surface. We assume the source for luminescence is a point-like dipole current linearly polarized along the x direction. The radiation caught by $\lambda/2$ aperture is transported to the tapered region clad with

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perfect conducting metal and then coupled to the ordinary waveguide (optical fiber). We run the simulation with time steps of $c\Delta t = \lambda/(40\sqrt{3})$ until the signal intensity $(|E_x|^2 + |E_y|^2 + |E_z|^2)$, which is evaluated at $(0, 0, 3.25\lambda)$, reaches steady state.

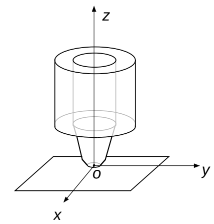

Fig. 1. Schematic picture of simulation for NSOM.

§3. Results

Figure 3 shows the calculated signal intensity as a function of the displacement of the probe from the origin. For both scans along x and y directions, the full width at half maximum of the signal (spatial resolution of NSOM) is estimated to be around 0.25λ, which is much smaller than the aperture diameter of $\lambda/2$. This performance is beyond the fundamental principle of NSOM and in good agreement with the experimental result. Through this preliminary calculation, we demonstrate that FDTD simulation is quite useful to understand the behavior of light in the near-field probe and to optimize its structure for advanced measurements.

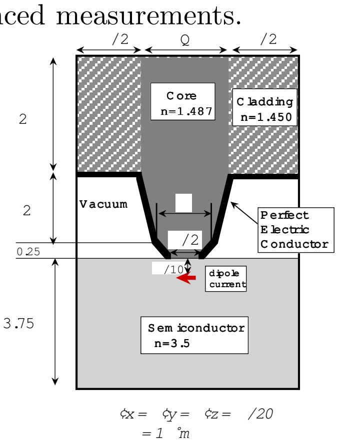

Fig. 2. Cross section diagram (xz-plane at $y = 0$) of the geometry in our 3D computer simulations for the double tapered fiber probe.

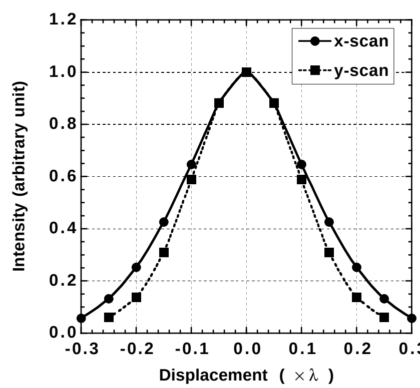

Fig. 3. Intensity vs. displacement from the origin o in Fig. 1. Closed circles and squares denote the total electric field intensity along x and y direction, respectively.

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